High Structural Efficiency SLMS™ for High Energy Laser Systems, Telescopes and Space Optics

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Outline

- Web vs Foam Structures
- Tap Test Results
- Comparison with Other Technologies
- VLA Coatings for High Energy Laser Systems
- SLMS™ Forecast
  - ⇒ Telescopes: Airborne and Space Borne Communications

Foam vs Web Structures For Lightweighting

Roles/Requirements	Foam	Webs
Support against polishing pressures	Fully distributed load paths under mirror surface, easier metrology mount	Concentrated load paths to print-through as lines, difficult metrology mount
Dynamics/stability/ stiffness/high modes	Higher stiffness, first mode frequency	More mass for same stiffness, first modes
1-g sag (proportional to pocket width)	Pockets = 10 microns	Pockets = 100,000 microns
Micrometeoroid protection	Natural bumper material and ripstop	Little or none
Reliability/ Redundancy	Many alternate load paths - graceful crush fail	Structural failure effect greater - catastrophic fail

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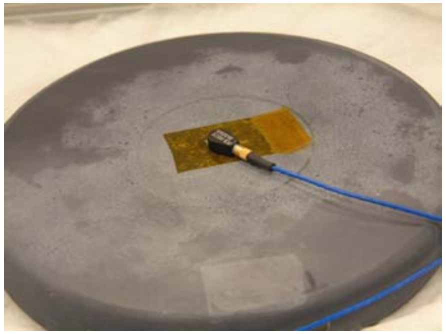
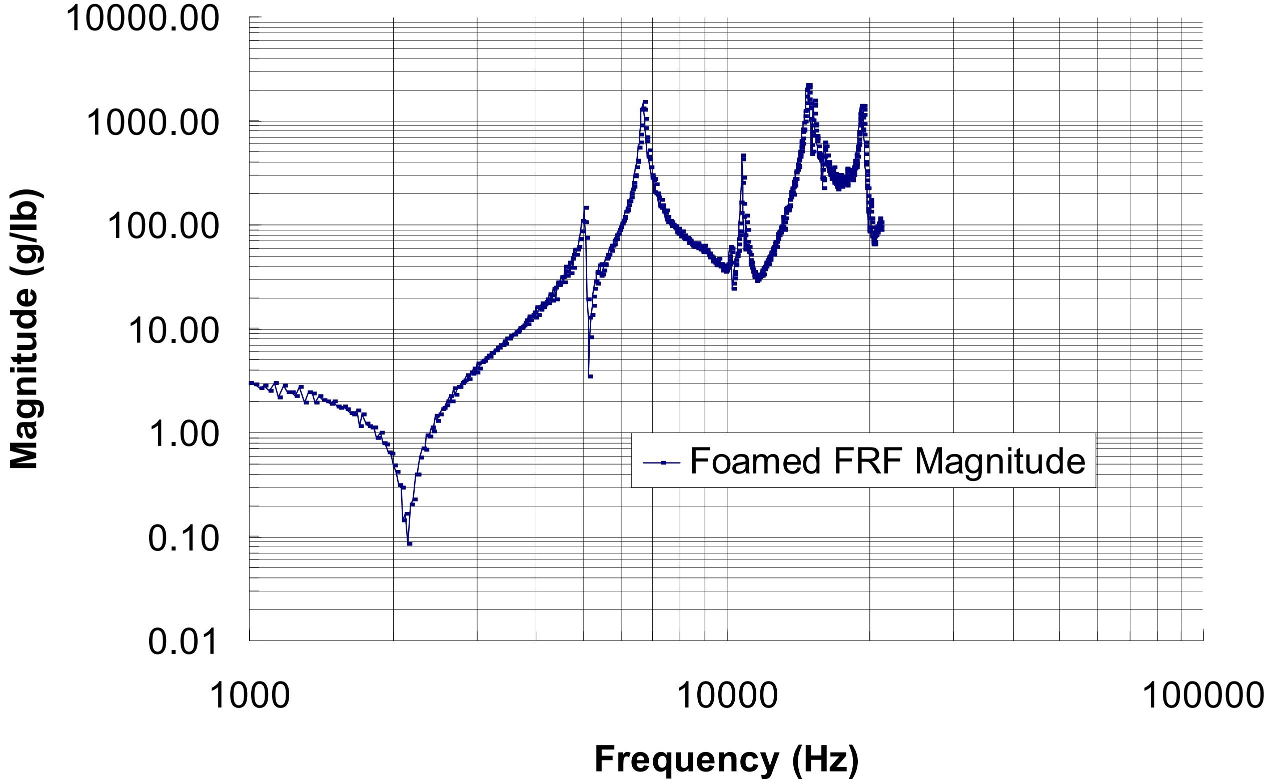
Tap Test Data



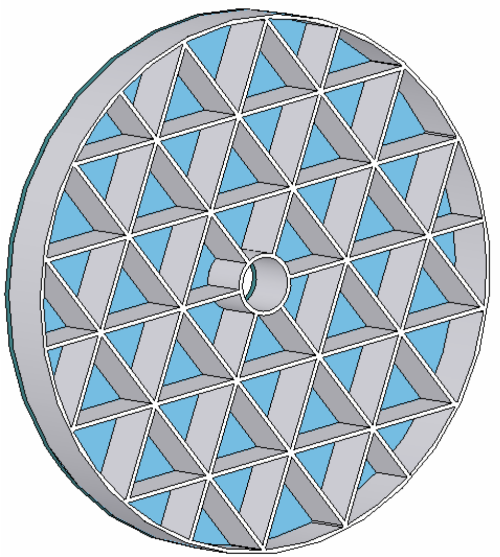
Data courtesy of Dennis Smith, ATA Sensors Albuquerque, New Mexico



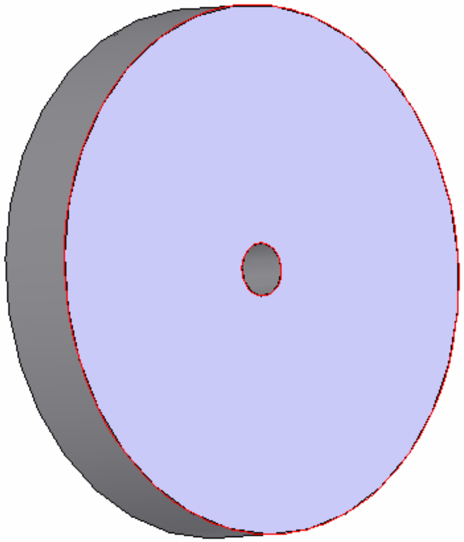
- 5 inch diameter sphere, 600 mm ROC, 10% relative density foam core, E_{foam} ~1% of E_{solid}, skin thickness ~0.01 inch
- First Mode observed at 4980 Hz (potato chip)
- First Frequency a function of Mirror Geometry (skin thickness, diameter, foam density, foam modulus)
- SiC-SLMS™ can provide >7 kHz first mode when mounted
- Either Technology Suited for Fast-Steering Mirrors (HEL Systems, Relay Mirrors)

Comparison of SLMS™ With Other SOTA Mirrors: 1st Frequency and Areal Density

- Compared SLMS™ with ULE, Zerodur and Beryllium:I70 lightweighted mirrors
- Common geometry for lightweighted mirrors– did NOT try to minimize areal density, maximize frequency or otherwise optimize the designs – picked a believable configuration
- Did try to match SiC-SLMS™ performance to the Beryllium mirror



Material	Young's Modulus	Density
	(GPa)	(kg/m^3)
ULE	67	2210
Zerodur	92	2530
Beryllium	287	1850
SLMS (skin)	130	2330
SLMS (10% foam)	1.3	233



Be, ULE, Zerodur

SLMS™

	Outer Diameter	Center Hole Diameter	Facesheet Thickness	Depth	Web Thickness
	(mm, inch)	(mm, inch)	(mm, inch)	(mm, inch)	(mm,inch)
Be, ULE Zerodur	250, 9.84	25.0, 0.984	3.3, 0.13	25.4, 1.0	3, 0.118
SLMS™	250, 9.84	25.0, 0.984	0.64, 0.025	39.1, 1.54	N/A

Trade Study Results: SLMS™ Have High Structural Efficiency

- Picked believable non-optimized design for comparison – an optimized SLMS™ can perform even better than Beryllium

Mirror	1st frequency (kHz)	Mass (kg)	Areal Density (kg/m^2)
ULE	1.76	0.98	16.1
Zerodur	1.93	1.12	18.4
Beryllium	3.98	0.81	13.3
SLMS™ , 10% foam	3.72	0.65	10.7
SiC-SLMS™ , 10% foam	3.98	0.82	13.3

- SLMS™ has 93.5% 1st Frequency of Be, at 80% the weight of Be
- SiC-SLMS™ Matched 1st Frequency of Be at Same Weight
- Both SLMS™ Have ~2X 1st Frequency at lower areal density than ULE and Zerodur
- Cost to polish SLMS™ same as for glass: 0.005 waves rms HeNe with <2 Angstroms rms finish and 20/10 scratch/dig has been demonstrated on plano
- No issue of print-through: NASA/UAH showed repeatable cryo-stability of 3.7 nm rms at 27K
- Schedule to Produce SLMS™ <20 weeks for most applications
- 1st Frequency >5000 Hz possible with Silicon and SiC-SLMS™: Low Moment of Inertia is Ideal for High Bandwidth Fast Steering Mirror Applications – SLMS™ can provide >5X substrate weight savings with no penalty to frequency

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Where Would We Be Without Another Mirror Properties Table?

If you can read this you are using a telescope!

	ρ	E	E/ρ	σ_t	σ_t/ρ	α	k	C_p	$D=k/\rho C_p$	α/k	α/D	ν
Room Temperature Property:	**Density**	**Young's Modulus**	**Specific Stiffness**	**Tensile Strength**	**Specific Strength**	**Thermal Expansion**	**Thermal Conductivity**	**Specific Heat**	**Thermal Diffusivity**	**Steady State Distortion**	**Transient Distortion**	**Poisson's Ratio**
Units:	kg/m^3	GPa	$MPa\text{-}m^3/kg$	Mpa	$MPa\text{-}m^3/kg$	$10^{-6}/K$	W/m-K	j/kg-K	$10^{-6}/m^2/s$	µm/W	$s/m^2\text{-}K$	arbitrary
Preferred Value:	**Small**	**Large**	**Large**	**Large**	**Large**	**Small**	**Large**	**Large**	**Large**	**Small**	**Small**	
Fused Silica	2190	73	33		0.00	0.5	1.4	750	0.85	0.36	0.59	
ULE Fused Silica	2210	67	30		0.00	0.015	1.3	770	0.76	0.01	0.02	
Zerodur	2530	92	36		0.00	-0.09	1.6	810	0.78	-0.06	-0.12	
Beryllium:I-70	1850	287	155	237	0.13	11.3	216	1920	60.81	0.05	0.19	0.25
Silicon SLMS™ Skin	2330	130	56	120	0.05	2.5	148	750	84.69	0.02	0.03	0.24
Beta-SiC-SLMS™ Skin	3210	465	145	470	0.15	2.2	300	640	146.03	0.01	0.02	0.21
SiC: Sintered (alpha)	3100	410	132		0.00	4.02	125	670	60.18	0.03	0.07	0.14
SiC: Reaction Bonded	2950	364	123	300	0.10	2.44	172	670	87.02	0.01	0.03	0.18
Aluminum:6061	2700	68	25	276	0.10	22.5	167	900	68.72	0.13	0.33	0.33
Aluminum:7075 T6	2740	71	26	503	0.18	26	121	1000	44.16	0.21	0.59	0.33
Copper	8940	117	13	195	0.02	16.5	391	380	115.09	0.04	0.14	0.36
Invar 36	8050	141	18	276	0.03	1	10.4	520	2.48	0.10	0.40	0.26

- For High Energy Laser Applications Steady State and Transient Distortion are Key Figures of Merit – But They Don't Tell All!
- Low Thermal Diffusivity Glass and Glass Ceramics Irradiance Map Under High Power– Can Dramatically Impact System Wavefront Error and Beam Quality– Can Stress Deformable and Fast Steering Mirrors
- Uncooled Silicon Optics with Very Low Absorption Coatings were the breakthrough technologies for SBL and THEL programs

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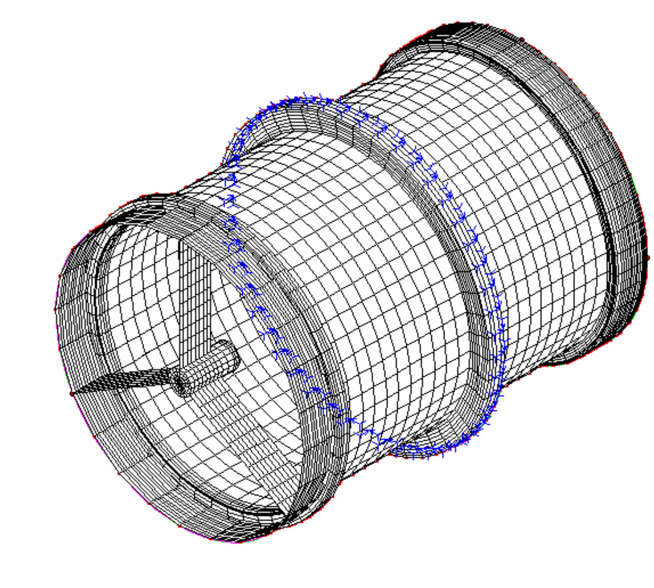
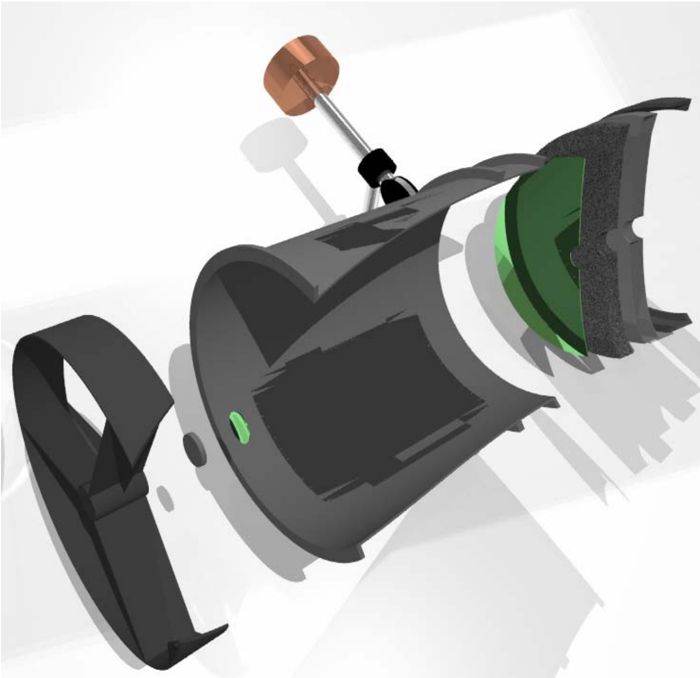
VLA Coatings For HEL IR Applications

- Successfully applied HEL mirror Very Low Absorption (VLA) coating to SLMS™
- 2.7-3.0 micron bandwidth
- 1.315 micron low-stress coating, validated at 27 Kelvin
- We have Communications Hybrid Optical RF Dish, CHORD™ Technology for Transformational Communications that separate RF (Ka, Ku-band) and Optical Signals

Schafer IR&D LASIT™ Project – Space Telescope

- LASIT™: a 25-cm Lightweight Athermal SLMS Innovative Telescope based on SLMS™ Primary mirror, single crystal silicon secondary, and Cesic® supporting structure
- Objective: Vacuum Cryo-Test to demonstrate TRL 6 for an Instrument
- Critical Demonstration for Cryo- and Space Based Telescope instrument manufacturers





IRD LASIT™ Weight Breakdown

Densities of Materials

Silicon Foam	0.23	g/cm3	Foam can be tailored to a designated percent of solid silicon
Solid Silicon Closeout	2.33	g/cm3	
C/SiC	2.72	g/cm3	

Volume

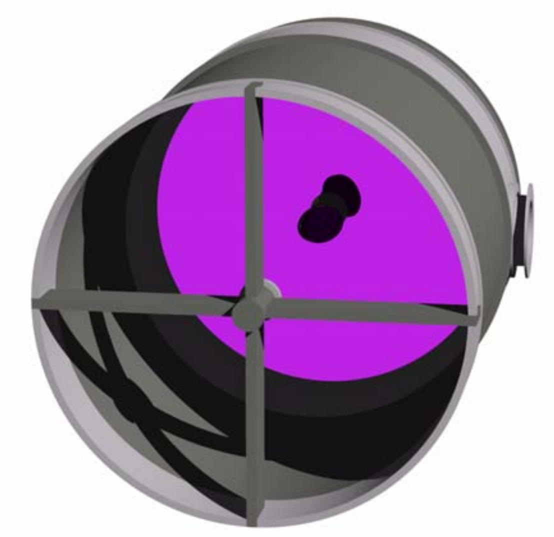
Primary Foam	1585.6764	cm3	foam
Primary Closeout	163.8019	cm3	closeout
Barrel	1024.4522	cm3	C/SiC
PrimarySupportCup	134.3467	cm3	C/SiC
SpiderSupport	164.7103	cm3	C/SiC
SecondaryMirror	4.0441	cm3	solid silicon (closeout material)

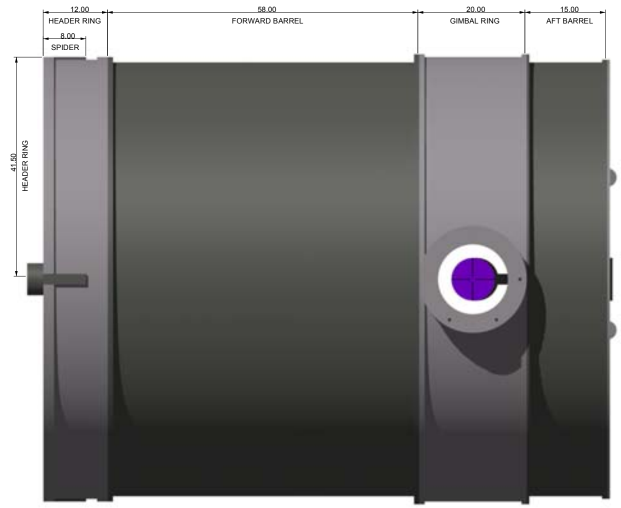
Weight

Primary Foam	369.46	g
Primary Closeout	381.66	g
Barrel	2786.51	g
PrimarySupportCup	365.42	g
SpiderSupport	448.01	g
SecondaryMirror	9.42	g
Total Telescope	**4360.49**	**g**
	9.61	**lb**

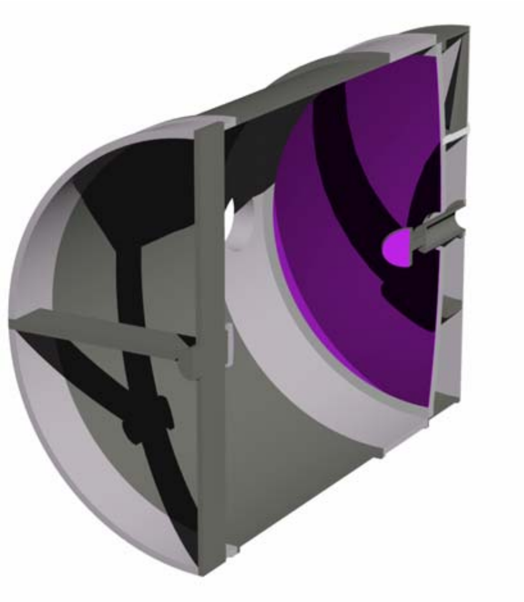
Airborne Relay Mirror 75 cm Telescope Concept

- Lightweight Athermal SLMS Innovative Telescope (LASIT™)





Full Telescope – Side View – With Dimensions (units are centimeters)



Aperture	75.00	cm
Focal Ratio	1.25	no dim (f/#)
Focal Length	93.75	cm
Focal Length of Primary	93.75	cm
Magnification	9.00	no dim
Focal Length of Secondary	10.42	cm
Aperture of BCM Optics	8.33	cm
Inner Diameter of Primary	8.00	cm

75 cm LASIT™

Primary Mirror

Subtotal One Sector		1834.71	4.05	
Total 3 Sectors		**5504.12**	**12.14**	

Other Mirrors

Volume	**Part #**			
Secondary Mirror	11	85.93	cm3	solid silicon
Tertiary Coude Turning Flat	12	71.09	cm3	solid silicon

Weight		**grams**	**lb**
Secondary Mirror	11	200.22	0.44
Tertiary Coude Turning Flat	12	165.63	0.37

Telescope Assembly

Volume				
Gimbal Ring	13	7544.05	cm3	C/SiC
Forward Barrel	14	7980.43	cm3	C/SiC
Aft Barrel	15	3199.32	cm3	C/SiC
Head Ring	16	3499.98	cm3	C/SiC
Spider Assembly	17	2806.85	cm3	C/SiC
Gimbal Bearing Flange 1	18	562.56	cm3	C/SiC
Gimbal Bearing Flange 2	18	562.56	cm3	C/SiC
Aft Plate	19	2626.37	cm3	C/SiC
Tertiary Support Tower	20	358.93	cm3	C/SiC

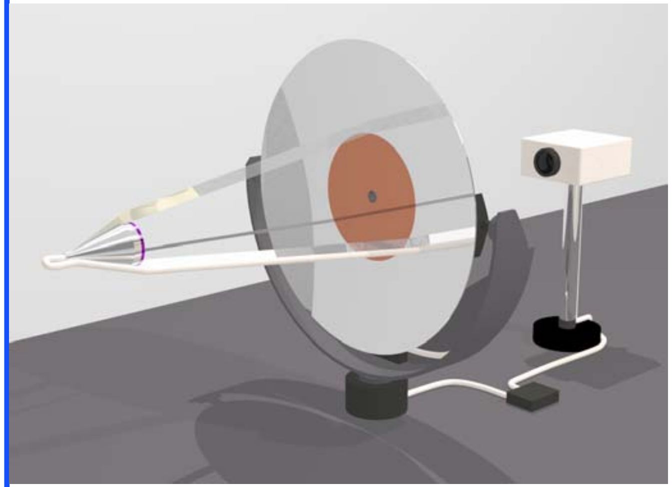
Weight		**grams**	**lb**
Gimbal Ring	13	18860.12	41.59
Forward Barrel	14	19951.08	43.99
Aft Barrel	15	7998.30	17.64
Head Ring	16	8749.96	19.29
Spider Assembly	17	7017.11	15.47
Gimbal Bearing Flange 1	18	1406.40	3.10
Gimbal Bearing Flange 2	18	1406.40	3.10
Aft Plate	19	6565.93	14.48
Tertiary Support Tower	20	211.86	0.47

	grams	**lb**
Mirrors		
Primary	5504.12	12.14
Secondary	200.22	0.44
Tertiary	165.63	0.37
Subtotal	**5869.97**	**12.94**
Telescope Assembly	**72167.15**	**159.13**
Total	**78037.12**	**172.07**

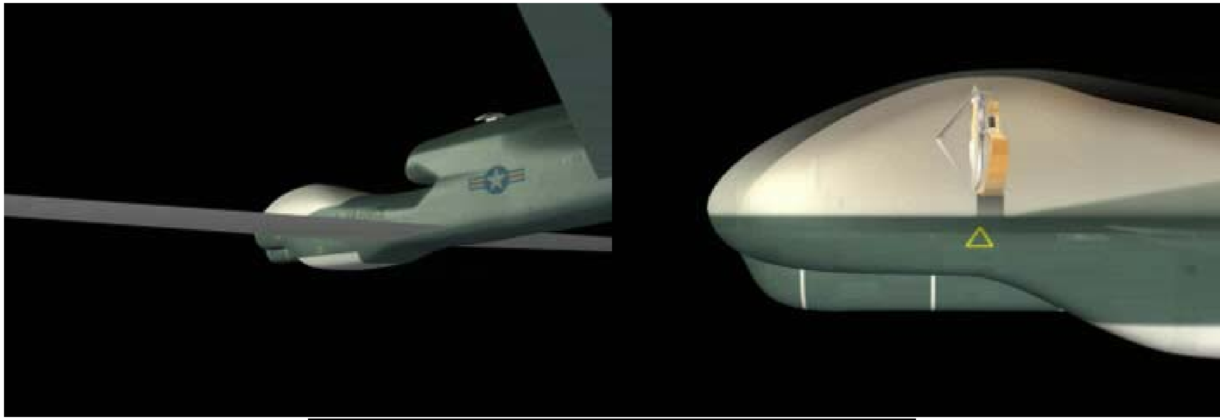
- **Weight can be further reduced using new structural materials**
- **AFRL/ML Phase I and AFRL/VS Phase II SBIRs will evaluate SLMS™ with new materials**

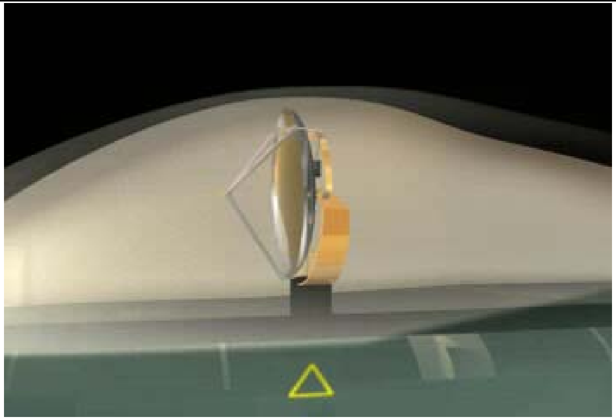
Subscale CHORD™ Preliminary Design

- Communications Hybrid Optical RF Dish (CHORD™)
    - Transformational Communications at 1.55 μm and Ku-Ka Bands
- Producing under AFRL/SNJ Phase II – On-Track for December CDR



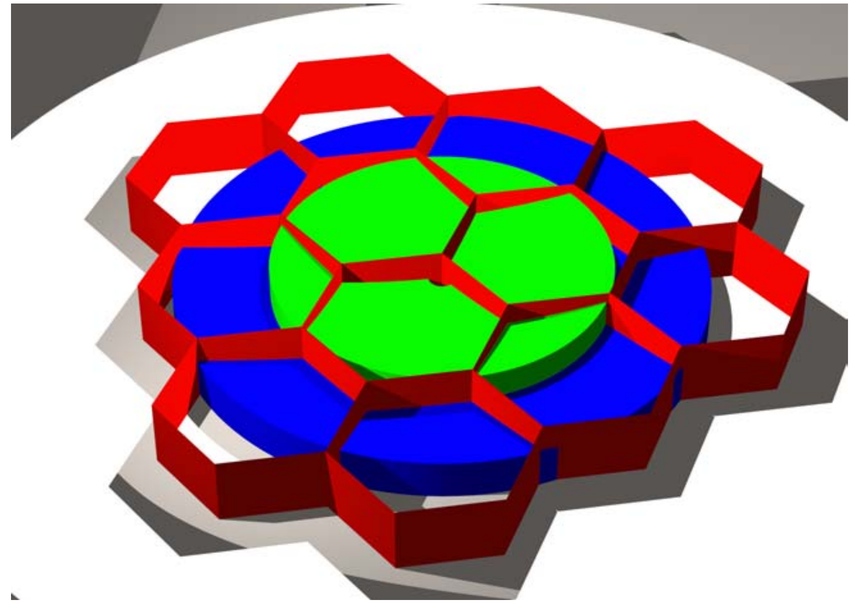
- 5/12 scale CHORD™ shown with Azimuthal/Elevation (2-axes) gimbal and IR detector – test range can supply 3rd axis of rotation





Road Map to 1.5 m Bonded Primary Mirror

- Current Manufacturing Infrastructure Limited to ~56 cm Physical Aperture
  - ⇒ 56cm Hexes vs 1.5m



- Non-recurring Manufacturing Savings >$5M compared to 1.5 m Production Facilities
- Would weigh 125 pounds
- Joining Processes for Silicon Are Established and Well Understood
- Bonded Silicon Optics for HELs were Demonstrated in 1995, 1996, 1997, and 2001 in sizes up to 53 cm
- SBL IFX had planned a 2002 Braze Demonstration of an 1.1 meter diameter silicon annular optic with 8 segments

SLMS™ Forecast – What's Next?

- Proposals to NASA to Demonstrate Bonded SLMS™ for EUV, Far Infrared and Submillimeter Applications
- Actively pursuing Major Systems Houses with High Energy Laser Programs, Airborne and Space Telescopes Applications
  - ⇒ On-Axis and Off-Axis Aspheres